INT. J. BIOAUTOMATION, 2016, **20**(3), 389-406

Changes in EMG Activities of Upper Arm Muscles and in Shoulder Joint Angles in Post-stroke Patients

Rositsa Raikova[1*], Silvija Angelova[1], Simeon Ribagin[2]

[1]*Department of Biomechanics and Control of Movements*
Institute of Biophysics and Biomedical Engineering, Bulgarian Academy of Sciences
105 Acad. G. Bonchev Str., Sofia 1113, Bulgaria
E-mails: rosi.raikova@biomed.bas.bg, sis21@abv.bg

[2]*Department of Bioinformatics and Mathematical Modelling*
Institute of Biophysics and Biomedical Engineering, Bulgarian Academy of Sciences
105 Acad. G. Bonchev Str., Sofia 1113, Bulgaria
E-mail: sim_ribagin@mail.bg

[*]*Corresponding author*

Received: January 11, 2016 **Accepted: September 10, 2016**

Published: September 30, 2016

Abstract: *The aim of the paper is to compare the electromyographic signals (EMGs) and the joint angles of the affected upper limb muscles of stroke survivors to those of their non-affected limb as well as to those of the dominant and the non-dominant limbs of healthy volunteers. Twenty five volunteers, ten post-stroke survivors and fifteen healthy subjects as control group, participated in the experiments. EMGs of muscles of the upper limbs and two angles in the shoulder joint were registered and processed during three static and two dynamic tasks. The results showed a big variability of all investigated parameters (mean and median frequencies, ranges of motions, maximal normalized EMGs) both for the patients and for the healthy subjects, for right and for left hand. This makes difficult a deduction of definitive conclusions about the changes in motor control of the upper limbs due to stroke. Moreover, natural differences in motor control exist for dominant and non-dominant limb. On the whole, the power-frequency analysis and the relevant statistical analysis indicated that the muscles of the affected limb had lower median frequencies than those of the healthy limb. Examination of full elbow flexions in the sagittal plane showed that the range of the motion in the shoulder joint of both limbs of the patients increased when compared to the healthy subjects and that this increase was larger for the affected limb. The post-stroke survivors used more of their muscle power although no increased co-contraction was observed.*

Keywords: *Post-stroke survivors, EMG, Power spectrum, Median frequency, Muscle coordination.*

Introduction

After a motor neuron injury such as a stroke, there are functional changes in the brain, and, consequently, in the muscle motor unit activity. It is established that the relationship between motoneuron size and the number and the size of the muscle fibers it innervates is lost or damaged, and reorganization (known as neuroplasticity) of this relationship occurs because of interrupted descending pathways [14, 18]. The loss of muscle mass of the impaired limb is due to a reduction of the number, size and type of motor units [10]. The motor units' synchronization is disturbed [7] and a decrease of the motor units' firing rate is also reported [8, 11, 17]. Brain damage results in corticospinal and supraspinal motor pathway disruption and possibly leads to synaptic degeneration at the segmental level [15]. This loss of neural signaling results in motor neuron loss and altered force control mechanisms.

Besides changes at the motor unit level in the damaged post-stroke patients' limbs, for which changes can be presumed by measuring surface or intramuscular electromyographic signals, other alterations related to the whole muscle function and muscle and movement coordination are also observed [5, 25]. Levin [13], examining reaching movements in the horizontal plane, found that patients with hemiparesis had abnormalities in inter-joint coordination, estimated by the degree of correlation between the elbow and shoulder excursion. It is hypothesized that the observed abnormal synergies in the upper limbs [2] are probably caused by abnormal co-activation of muscles [22]. Because of this, patients cannot exercise independent joint control during movement.

It is difficult to make consistent conclusions from researches involving impaired muscle control in post-stroke survivors due to several reasons. Some of them are: a limited number of subjects, wide variation of patient ages, different causes and duration of lesions, different places and areas of damaged brain tissue, etc. Besides these reasons, the differences in the motor control of the dominant and the non-dominant upper limb [6] have to be taken into account since stroke can injure either the left or the right limb. Therefore, the question as to whether the lack of muscular control is due to disruption at the supraspinal level, intrinsic changes in the motor neuron pool, or changes in the properties of the muscle itself, remains unanswered.

The aim of the paper is to compare healthy and damaged (dominant and non-dominant, respectively) upper limb muscles' functioning of post stroke survivors and healthy subjects. Experiments were performed with 10 post-stroke survivors and 15 healthy volunteers. Power spectral analysis of surface electromyography signals (EMGs) was performed for several upper limb muscles during a static task. Two shoulder angles (flexion/extension and abduction/adduction) and normalized EMGs of main surface muscles were studied during maximal elbow flexions in the sagittal plane with and without additional load at the wrist. Statistical analysis was performed aiming to establish statistical reliability of the observed changes in the investigated parameters median frequency and range of motion.

Materials and methods

Experiments

The experimental procedure was described in detail in [1, 21]. All participants filled in an injury card (including personal data, anthropometrical data – height, weight, etc.), and after they were informed in details about the aim of the experiments, they gave informed consent. The experimental procedure was approved by the Scientific Council of the Institute of Biophysics and Biomedical Engineering. During all tasks, the participants were seated in a chair without an elbow-rest. They received verbal instructions prior to each of the tasks and a visual demonstration during task execution, including short and stimulation commands, was done. From the performed ten motor tasks, first with the dominant upper limb (for healthy volunteers) and, respectively, with the healthy upper limb (for post stroke survivors) and after that with the non-dominant, respectively, with the affected upper limb, only experimental data of five motor tasks is presented in the paper. The static task, named further as "fatigue", consisted of maintaining a posture – stretching the arm forward in the horizontal plane for one minute. The motions included three trials of maximal elbow flexion in the sagittal plane, starting from a fully extended downwards arm, without and with a load of 0.5 kg placed on the wrist (named ***FSP*** and ***FSP+load***, respectively). Two additional tasks, maximal isometric contractions against resistance and maximal isometric contractions with a dynamometer (the balloon of the dynamometer was put in the examined hand and the subject was asked to squeeze it to the highest degree) were recorded, aiming to ensure maximal isometric forces of the investigated muscles for further normalization. The 8-channel telemetric system Telemyo 2400G2 of Noraxon Inc. was used for on-line monitoring and saving the experimental data for further off-line processing. The surface EMG signals were taken away by Ag/AgCl circle electrodes "Skintact-premier" F-301. The two angles of the shoulder joint (flexion/extension and abduction/adduction) were measured using a 2D flexible electrical goniometer. The sampling frequency was 1500 Hz and the duration of each motor task was one minute. The investigated muscles were: pars acromialis, pars clavicularis and pars spinata of m. deltoideus (**DELacr, DELcla, DELspi**); m. biceps brachii (**BIC**); caput lateralis and caput longum of m. triceps brachii (**TRIlat, TRIlong**) and m. brachioradialis (**BRD**). For some of the investigated subjects, instead of EMGs of the m. **TRIlat** (which was decided to be not as informative as **TRIlong** and duplicated its functions), two angles of the shoulder joint (flexion/extension and abduction/adduction, i.e. α_1 and α_2) were measured. A PC camera monitored and stored the subjects' behavior during the experiments.

All 15 healthy volunteers were right handed, 6 of them were men. Eleven volunteers were involved in the experiments including a goniometer. Seven post-stroke patients were men. The first 8 patients had stroke at the left side and the affected limb was the right one. For the remaining two patients opposite cases were documented. The first 8 patients participated in the experiments where the two angles in the shoulder were measured. Two of the post-stroke survivors (the last two) were left-handed. The prescription of the incident for the first four patients was about 3 years, for the fifth patient – about 9 years, for the sixth – 6 months, for the seventh – about 2.5 years, for the eight – 6 months, for the ninth – 1 year and for the tenth – 3 months. All patients can walk without help and can perform the motor tasks satisfactory with both arms.

Signal processing

The non-processed data, saved in a text format, was input to a custom-made program written in MATLAB. The EMG signals were initially filtered (two specially designed high-pass Butterworth filters removing QRS complexes; one band-pass filter removing 50 Hz influence of the electrical set; one low-pass Butterworth filter with cut-off frequency of 20 Hz removing noise and one high-pass Butterworth filter with cut-off frequency of 350 Hz) [21]. For the static task "fatigue", power spectral analysis was performed and mean and median frequencies [19] were calculated. Two time intervals of 5 s were chosen for this purpose – one at the beginning of the task (often between the 5 s and the 10 s) and one at the end of the task (often between the 50 s and the 55 s). The reason for choosing these intervals was avoiding artifacts, which was visually controlled. The second time period was chosen in order to investigate the presence of muscle fatigue, which was documented by the observation of the flexion angle in the shoulder joint, which nearly always decreased at the end of the maintenance of the required posture. The mean (***MNF***) and the median frequency (***MDF***) were calculated and the ***MDF*** is the frequency which divides the area under the power – frequency function in halves.

For the investigated flexion motions (***FSP*** and ***FSP+load***), after filtration, rectification and smoothing (151 samples, 0.1 s time interval), a normalization of the EMGs was performed. For this purpose, the maximal values of each of the EMG channels were calculated using the two maximal isometric tasks, and the EMGs during motion were normalized to these values. Then, for one chosen attempt for only the flexion part of the motion (determined from the beginning of the angle changes to reaching maximal values of the shoulder flexion), the maximal amplitudes and the time moments when these maxima were reached were calculated for each muscle. The ranges of the two angles (the difference between their maximal and minimal values for a chosen attempt) were also calculated.

Statistical analysis

In order to determine the possible differences between the ***MNF*** and ***MDF*** of the respective muscles of the non-affected and of the affected limbs for all 8 patients with right injured limb statistical test was performed using MedCalc (MedCalc Statistical Software, version 15.11.0, Ostend, Belgium; https://www.medcalc.org). Paired *t*-test was used to detect statistical significance of differences in the activities between the affected and the non-affected arm. The dependent variables were the ***MDF*** or ***MNF*** values of the muscles obtained from the affected and the non-affected arm at the beginning and at the end of the motor task (when eventually fatigue was expected). The same approach was used to determine statistical significance in differences in the ***MDF*** and ***MNF*** values between the dominant and the non-dominant limbs of the 15 healthy subjects. Independent samples *t*-test was used to compare the range of motion of the shoulder joint during the elbow flexion in the sagittal plane between healthy subjects and post-stroke patients. The *p*-value was considered significant for $p < 0.05$.

Results

The results from 25 participants in the experiments are presented. Fifteen of them were healthy subjects (Sub1, Sub2, …, Sub15), all right-handed, average age 37.6 years. For 11 of them, two shoulder angles (flexion/extension and abduction/adduction) were measured instead of the EMGs of the muscle **TRIlat**. The experimental data of ten post-stroke patients (Pat1, Pat2, …, Pat10), with average age 53.9 years, was included in this study. The first eight had lesions at the left hemisphere, i.e. the affected limb was the right one. With the exception of Pat5 and Pat6, which were left-handed, all the remaining ones were right-handed. For the first eight patients from the used 8 channels 6 were for EMGs and two for the two shoulder angles. The last two patients were investigated without using the goniometer – hence all 7 channels registered EMGs.

Since the EMGs of the muscle **TRIlat** for some of the investigated subjects (8 post-stroke patients and 11 healthy volunteers) were replaced by the signals from the goniometer, only the results from the remaining 6 muscles were presented further for all volunteers, aiming to investigate power/frequency distribution.

Summary data from the performed frequency analysis for all volunteers, with the excerption of the last two patients which injured limb is the left one, is presented in Table 1. As many authors mention [19] the calculated ***MNF*** values were always higher than those of the ***MDF*** and so much informative than ***MDF***, so we will concentrate further mainly on the ***MDF***. The range of the calculated frequencies is very wide – from 38 Hz to 116 Hz (Table 1). The average values of the ***MDF*** for the right hand were always lower than for the left hand for all muscles for the patients. For some muscles this was not valid for the healthy subjects and for them the values for both hands were very similar in contrast to post-stroke survivors. With the exception of m. **BRD** for the healthy subjects the average values of ***MDF*** decreased at the end of the task, which confirmed a presence of fatigue. The biggest differences between calculated minimal and maximal values were observed for m. **BIC** for both limbs.

Table 1. Statistics of the parameter ***MDF*** for the investigated volunteers, separately for the patients (the first 8 of them which have right injured limb) and for all 15 healthy subjects, during the task "fatigue" for the 6 muscles. The minimal, maximal and average values of ***MDF*** for the left and the right limbs are given in [Hz] and a recalculated for a 5 minute time period at the beginning and at the end of the motor task.

Patients	**Start of the task "fatigue"**						**End of the task "fatigue"**					
	MDF left limb			***MDF*** right limb			***MDF*** left limb			***MDF*** right limb		
	minimal	maximal	average	minimal	maximal	average	minimal	maximal	average	minimal	maximal	average
DELacr	69.5801	101.8066	80.41991	54.1992	94.4824	74.3408	57.1289	93.7500	76.3184	60.0586	94.4824	70.8252
DELcla	66.6504	93.7500	81.37207	54.9316	82.7637	69.2871	54.9316	88.6230	74.8535	43.2129	80.5664	66.2109
DELspi	64.4531	76.9043	69.7266	46.1426	72.5098	60.0586	46.8750	76.1719	65.8447	42.4805	74.7070	59.8389
BIC	55.6641	113.525	80.4932	43.9453	112.061	67.5293	55.6641	99.6094	68.4082	38.0859	114.9900	65.4785
TRIlong	56.3965	94.4824	79.9072	42.4805	99.6094	74.5606	72.5098	90.0879	80.9326	43.9453	90.8203	69.7998
BRD	58.5938	93.7500	78.8818	52.7344	94.4824	68.4082	51.2695	87.8906	78.3691	55.6641	84.2285	68.1885

Healthy subjects	**Start of the task "fatigue"**						**End of the task "fatigue"**					
	MDF left limb			***MDF*** right limb			***MDF*** left limb			***MDF*** right limb		
	minimal	maximal	average	minimal	maximal	average	minimal	maximal	average	minimal	maximal	average
DELacr	68.8477	92.2814	79.8337	62.2559	99.6094	78.7105	60.0586	93.0176	74.7070	57.8613	90.8203	74.0723
DELcla	62.2559	96.4887	79.2841	62.2569	96.8398	78.6728	63.7207	102.5390	77.9297	53.4668	86.4258	75.7812
DELspi	57.8613	79.8340	67.6185	54.9316	83.3970	67.7668	52.7344	68.8477	63.3789	55.6641	76.1719	63.9648
BIC	65.9180	111.3280	83.5625	57.8613	114.9840	81.2008	54.9316	106.2010	72.6074	45.4102	101.0740	73.7793
TRIlong	62.2559	116.4550	87.2477	73.2422	105.4690	87.6224	54.9316	109.8630	80.4199	56.3965	93.0176	76.4160
BRD	64.4531	103.2720	80.3056	51.2695	94.5411	76.2734	64.4531	103.2720	80.0293	64.4531	90.8203	76.7578

To show these observations more clearly and individually, two figures – Fig. 1 (for 10 patients) and Fig. 2 (for 15 healthy subjects) are presented. The differences between ***MDF*** of the respective muscles of the right and the left hand for all 10 patients (Fig. 1) have predominantly negative values (the most of the symbols are situated under zero line). For the end of the posture maintenance (Fig. 1B) the ranges of the differences become smaller. The biggest difference is observed for m. **BIC**. The same comparison has been made for healthy volunteers (Fig. 2) where the differences between ***MDF*** of the dominant and the non-dominant upper limb muscles are presented at the beginning of the posture (Fig. 2A) and at its end, when eventually muscle fatigue can occur (Fig. 2B). It can be seen a symmetrical distribution of the calculated values around zero line. MDF_{RH}-MDF_{LH} range of m. **BIC** is again the largest one. The range of the calculated values in Fig. 2B for the muscles **DELspi**, **BIC**, **TRIlong** and **BRD** decreases with respect to the results shown in Fig. 2A, which means that the ***MDF*** differences between right and left hand become smaller when a fatigue can be expected.

The statistical analysis has shown that a statistically significant difference ($p \leq 0.05$) between the ***MDF*** values of the affected and non-affected for all patients arms existed for the muscles **BIC**, **DELcla, DELspi,** and **TRIlat** in both time intervals – at the beginning (Table 2) and at the end (Table 3) of the posture maintenance. This difference is not significant at the start of the task for m. **BRD** but becomes significant at the end of the task, which suggests fatigue changes in this muscle, too. Note that here the differences are calculated between affected and non-affected limbs and the first eight patients have injured right limb, but the last two ones have left injured limb.

The same analysis was applied in order to compare the ***MDF*** values obtained for the muscles of all 15 healthy voluntaries between dominant and non-dominant upper limb. The analysis has shown no statistically significant difference in both time intervals, at the beginning and at the end of the posture maintenance (Table 3).

Naturally, during elbow flexion in the sagittal plane, a motion in the shoulder joint is present. There was a preliminary impression using visual examination of the experiments from the video files, that post-stroke patients use predominantly their shoulder joint, thus helping themselves to fulfill the tasks ***FSP*** and ***FSP+load***. This was confirmed by calculating the range of motions in the shoulder joint. It was obtained as the difference between the maximal and the minimal values of the angles α_1 and α_2 for one chosen attempt of full elbow flexion with and without additional load at the wrist. The results are summarized in Fig. 3. In general, both the ranges of the angles α_1 and α_2 are greater for the post-stroke patients (Fig. 3C and Fig. 3D) than for the healthy subjects (there are also exceptions), for whom there are no significant tendencies noticeable in the differences between the dominant (right) and the non-dominant (left) hand (Fig. 3A and Fig. 3B).

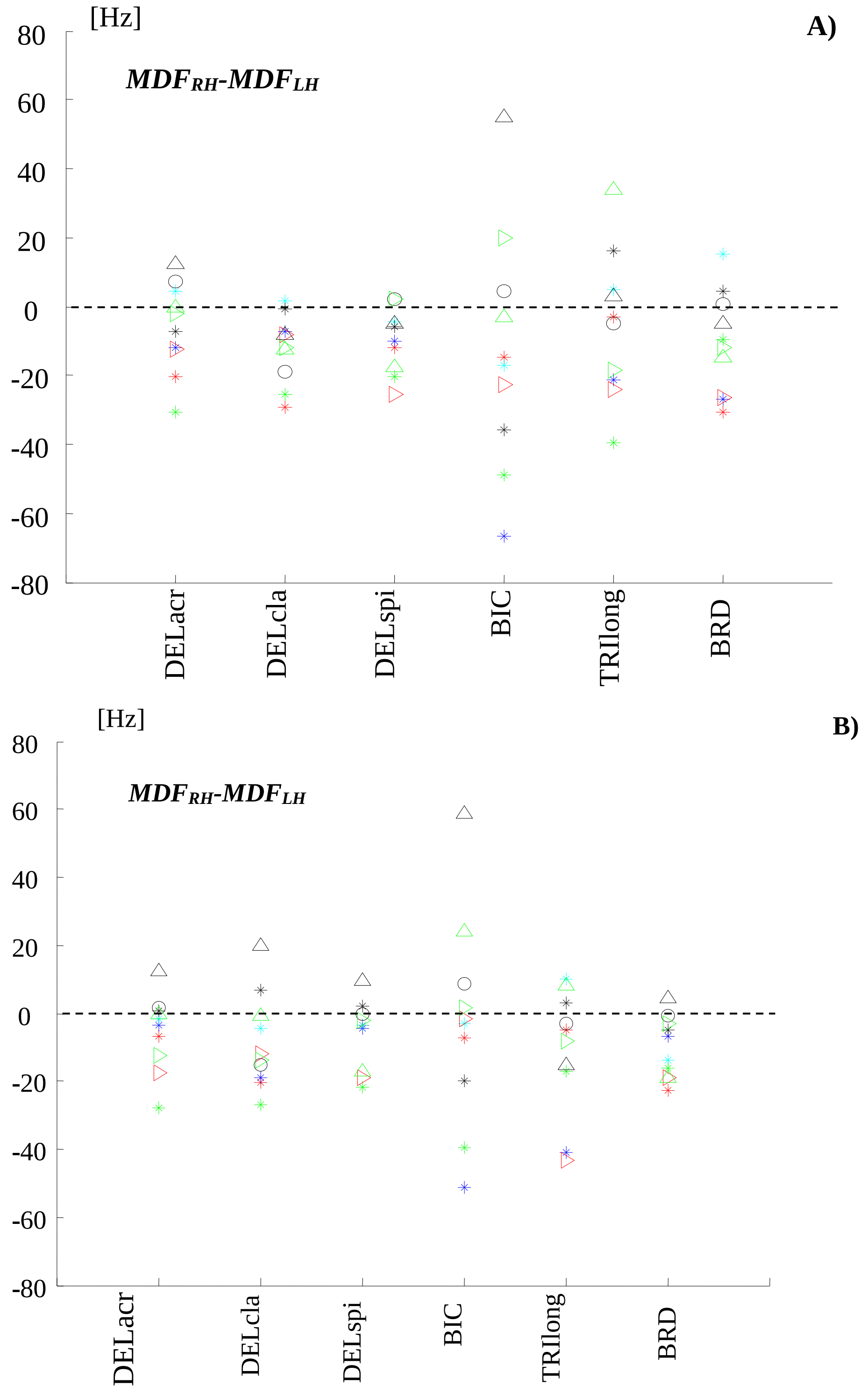

Fig. 1 Data for all 10 patients for the 6 muscles – the difference between ***MDF*** of the right (***MDF_{RH}***) and the left upper (***MDF_{LH}***) arm during the task "fatigue":
A) the ***MDF***s are calculated for an interval of 5s at the beginning of the task;
B) the ***MDF***s are calculated for an interval of 5s at the end of the task, i.e. when a presence of fatigue is observed. The following symbols are used: * Pat1, * Pat2, * Pat3, * Pat4, * Pat5, o Pat6, ▷ Pat7, ▷ Pat8, Δ Pat9, Δ Pat10.

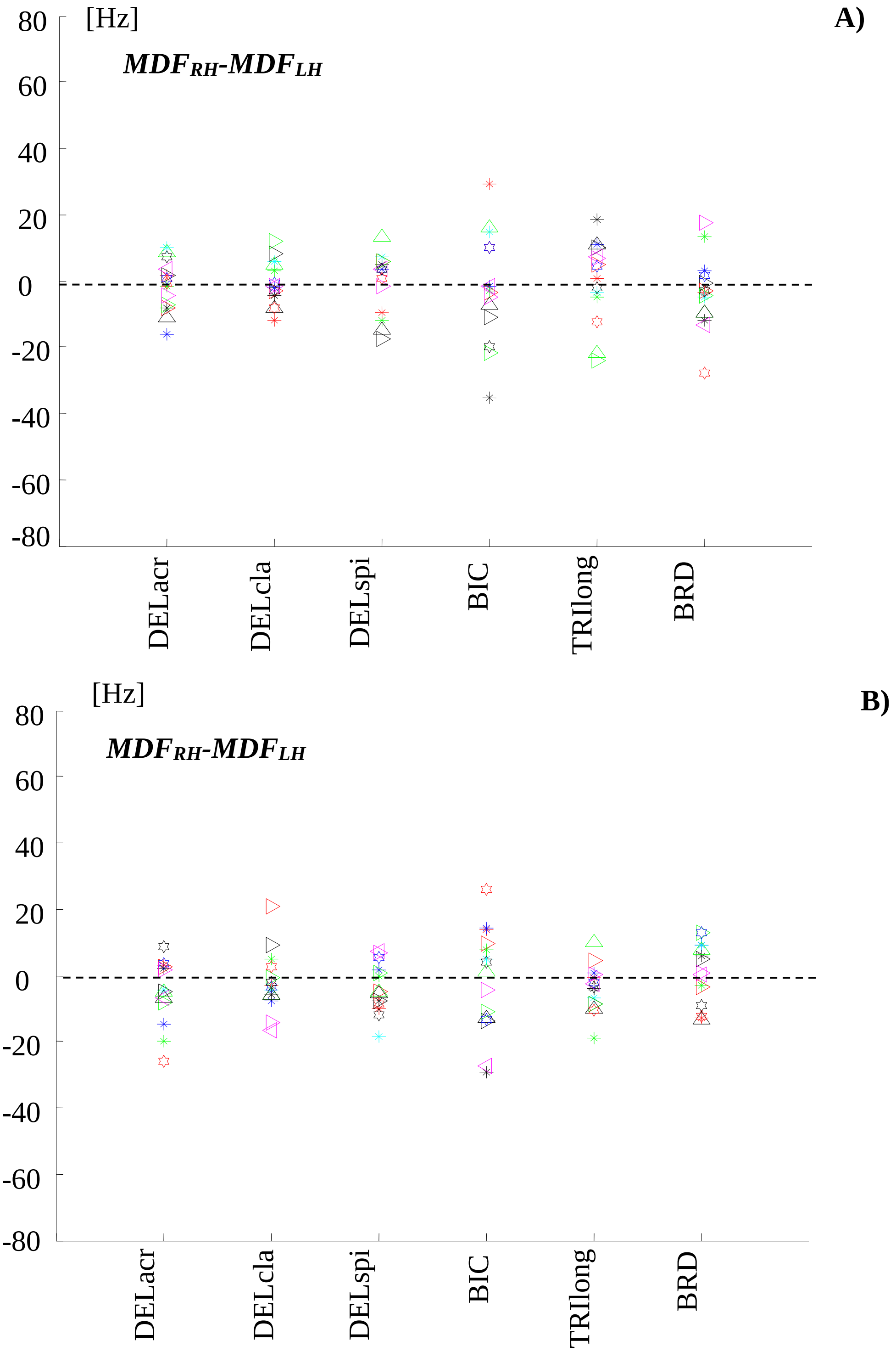

Fig. 2. Data for all 15 healthy volunteers for the 6 muscles – the difference between ***MDF*** of the right (***MDF$_{RH}$***) and the left (***MDF$_{LH}$***) upper arm during the task "fatigue".
A) the ***MDF****s* are calculated for an interval of 5 s at the beginning of the task;
B) the ***MDF****s* are calculated for an interval of 5s at the end of the task, i.e. when a presence of fatigue is observed. The following symbols are used: * Sub1, * Sub2, * Sub3, * Sub4, * Sub5, ▷ Sub6, ▷ Sub7, ▷ Sub8, Δ Sub9, Δ Sub10, ▷ Sub11, ◁ Sub12, ✡ Sub13, ✡ Sub14, ✡ Sub15.

Table 2. Statistical significance of differences in ***MDF*** obtained for the affected and the non-affected upper limb muscles (i.e. of MDF_{RH}-MDF_{LH}) of the first 8 post-stroke patients (for all of them the right hand was the injured one) for the task "fatigue"; "n.s." (not significant) $p > 0.05$, "*" (significant) $p < 0.05$.

Beginning of the motor task "fatigue"				
Muscle	**Mean**	**Standard error**	**T-value**	***p*-value**
DELacr	- 9.1553	6.9332	-1.3200	0.2078 n.s.
DELcla	-12.5427	5.0926	-2.4630	0.0274 *
DELspi	- 9.2468	3.7930	-2.4380	0.0143 *
BIC	25.6348	8.2003	3.1260	0.0074 *
TRIlong	21.0035	6.4494	3.2570	0.0139 *
BRD	8.8818	4.8524	1.8300	0.9053 *
End of the motor task "fatigue"				
Muscle	**Mean**	**Standard error**	**T-value**	***p*-value**
DELacr	8.4228	6.0334	-1.3960	0.1844 n.s.
DELcla	-12.7258	5.5581	-2.2900	0.0374 *
DELspi	6.5948	3.6773	1.7920	0.0473 *
BIC	14.0076	6.6553	2.1050	0.0499 *
TRIlong	13.0005	6.7654	1.9210	0.0376 *
BRD	-10.8948	3.8351	-2.8410	0.0131 *

Table 3. Statistical significance of differences between ***MDF*** obtained for the dominant and non-dominant hand (i.e. of MDF_{RH}-MDF_{LH}) of all 15 healthy subjects for the motor task "fatigue"; "n.s." (not significant) $p > 0.05$.

Beginning of the motor task "fatigue"				
Muscle	**Mean**	**Standard error**	**T-value**	***p*-value**
DELacr	-1.5625	3.2369	-0.4830	0.6331 n.s.
DELcla	-0.6836	3.3019	-0.2070	0.8375 n.s.
DELspi	-0.1465	2.4773	-0.0591	0.9533 n.s.
BIC	-1.9531	5.8206	-0.3360	0.7397 n.s.
TRIlong	0.3418	4.5448	0.0752	0.9406 n.s.
BRD	-3.7598	3.4500	-1.0900	0.2851 n.s.
End of the motor task "fatigue"				
Muscle	**Mean**	**Standard error**	**T-value**	***p*-value**
DELacr	-0.6348	3.6093	-0.1760	0.8617 n.s.
DELcla	-2.1484	3.8076	-0.5640	0.5771 n.s.
DELspi	0.5860	2.1461	0.2730	0.7868 n.s.
BIC	1.1719	5.0861	0.2300	0.8194 n.s.
TRIlong	-4.0039	4.2219	-0.9480	0.3511 n.s.
BRD	-3.2715	3.4195	-0.9570	0.3469 n.s.

The statistical analysis of the differences between the ranges of motions in the shoulder joint (flexion/extension and abduction/adduction) during the tasks ***FSP*** and ***FSP+load*** between healthy subjects and post-stroke patients (Table 4) showed that these differences were always statistically significant with the exception of one case – during performing the motion ***FSP*** with the left hand.

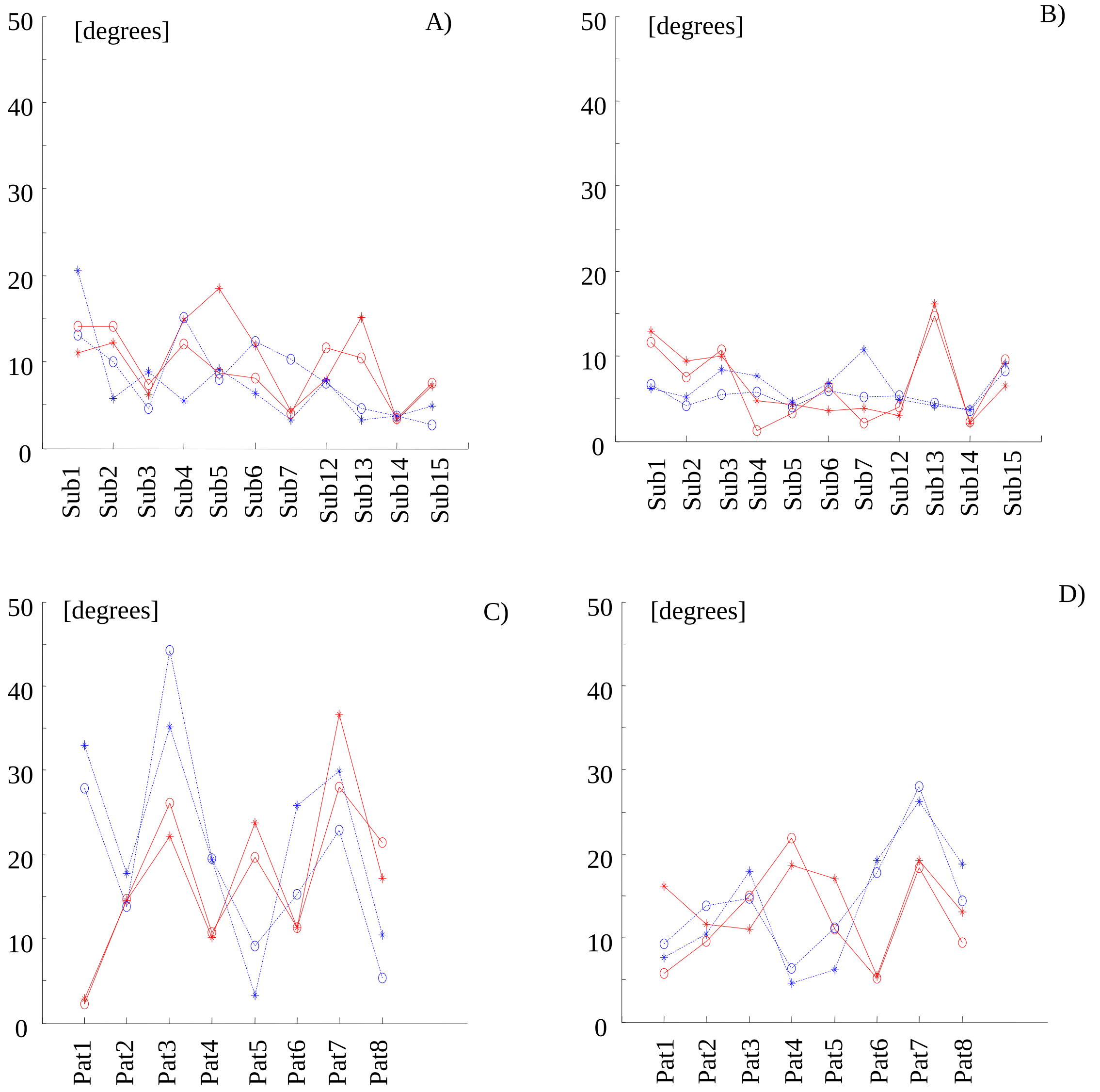

Fig. 3 The ranges of motions in the shoulder joint for 15 healthy volunteers and 10 patients for the tasks ***FSP*** and ***FSP+load***:
A) healthy volunteers, flexion/extension angle in the shoulder (α_1);
B) healthy volunteers, abduction/adduction angle in the shoulder (α_2);
C) post-stroke patients, flexion/extension angle in the shoulder (α_1);
D) post-stroke patients, abduction/adduction angle in the shoulder (α_2).
Used symbols: blue – right hand; red – left hand; '*' – elbow flexion in the sagittal plane without additional load, i.e. ***FSP***; 'o' – elbow flexion in the sagittal plane with additional load of 0.5 kg at the wrist, i.e. ***FSP+load***.
For all patients the injured limb is the right one, but Pat5 and Pat6 are left-handed ones.

Table 4. Statistical significance of differences in shoulder range of motion between all 15 healthy and the first 8 post-stroke subjects (with right injured limb) during the elbow flexion in the sagittal plane without (***FSP***) and with additional load of 0.5 kg placed on the wrist (***FSP+load***); "n.s." (not significant) $p > 0.05$, "*" (significant) $p < 0.05$.

Limb	**Motor task**	**Shoulder motion**	
Left	***FSP***	flexion/extension	n.s.
Left	***FSP+load***	flexion/extension	*
Left	***FSP***	abduction/adduction	*
Left	***FSP+load***	abduction/adduction	*
Right	***FSP***	flexion/extension	*
Right	***FSP+load***	flexion/extension	*
Right	***FSP***	abduction/adduction	*
Right	***FSP+load***	abduction/adduction	*

To investigate in details muscle coordination, one attempt of full elbow flexion with and without additional load was chosen for each investigated person. The beginning and the end of the flexion part of the motion was visually determined, based on the minimal and the maximal values of the two shoulder angles. The duration of the flexion motion was inspected using the video files, too. Within this time interval of the flexion motion, the maximal values of the processed (including normalization) EMGs of all 6 muscles were calculated together with the time moments when these maxima were reached. The time moment when **DELacr** reaches its maximal amplitude during elbow flexion is accepted as a zero moment (i.e. $t = 0$) for each patient. The remaining time moments are calculated with respect to this zero moment. The results from the 10 patients during flexion with load are presented in Fig. 4 both for affected (Fig. 4A) and non-affected (Fig. 4B) arms. The normalized amplitudes are bigger for the affected limb, especially for m. **BIC**.

Discussion

In accordance with findings of other researchers in this area, we ran into difficulties regarding the homogeneity of the group of the patients [9, 12, 20, 23, 24]. Some post-stroke survivors, who were potentially suitable candidates, refused to participate in the experiments because of different personal reasons. Many possible patients who wished to attend had to be rejected. Some of the exclusion criteria were: patients had to have a unilateral ischemic stroke lesion only; to be less than 70 years of age; to be able to fulfill all experimental tasks without any assistance; to have understandable speech; to have mild to moderate but not latent impairment; to have passed the acute phase; to be able to sign informed consent unaided; to have no other neurological diseases. However, post-stroke survivors who could perform very well the motions were well rehabilitated and the consequences from the stroke were not obvious. So, they were unsuitable for the aim of the experiments, too. The patients selected for the current investigation also did not form a very homogenous group, and this could not be avoided even after a long period of selection of possible participants in the experiments. The localization and the dimensions of the brain damage are different, naturally [20, 24]. The degree of recovery is also different [23] as it depends on patients' age and personal data (including smoking, high blood pressure and other diseases [12]) as well as on the method and time of rehabilitation. It has to be mentioned that we purposely included two left-handed patients to investigate the influence of handedness.

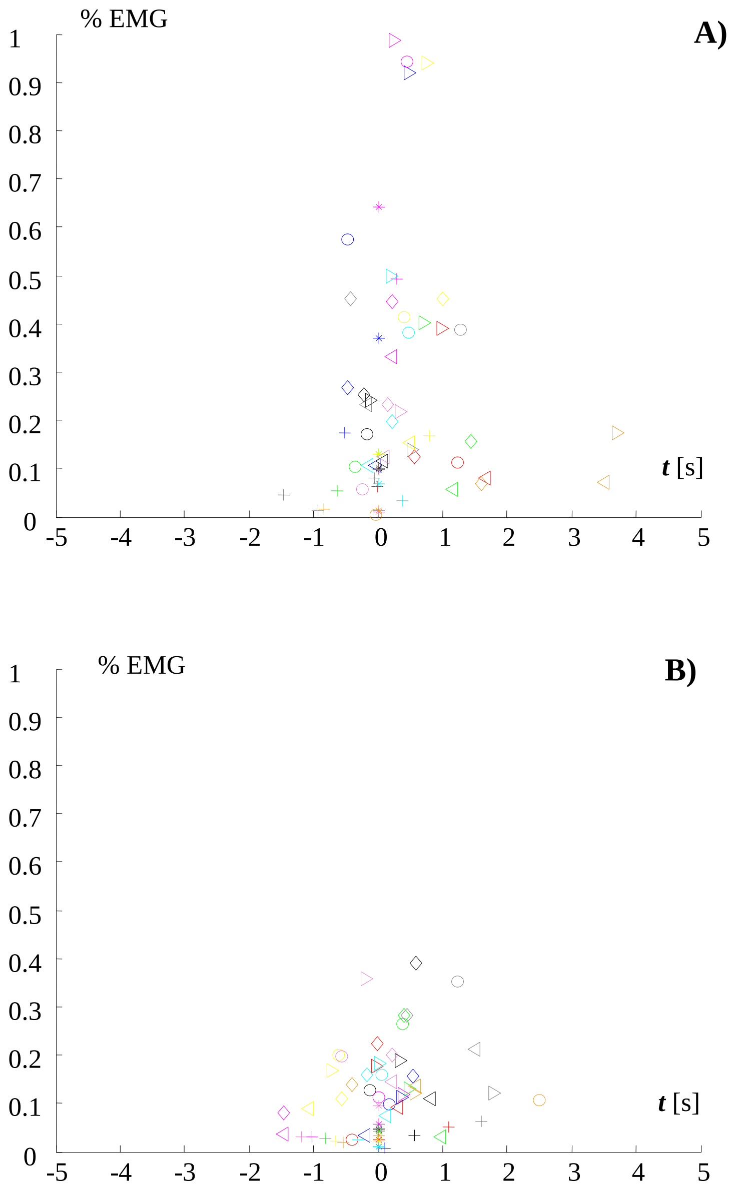

Fig. 4 Maximal values of the amplitude of the normalized EMG signals *f* or the 10 patients during flexions in the elbow joint in the sagittal plane with additional load, i.e. ***FSP+load***. The time moment when **DELacr** reaches its maximal amplitude during elbow flexion is accepted as a zero moment (i.e. *t* = 0) for each patient.
A) right (affected) limb; B) left (unaffected) limb.
The used symbols for the 6 muscles are as follows:
* – **DELacr**, o – **DELcla**, + – **DELspi**, ▹ – **BIC**, ◃ – **TRIlong**, ◊ – **BRD**.
Different colors are used for different patients.

The experiments were limited by the number of channels of our experimental Noraxon system. Some compromise had to be made. More channels, i.e. more cables, would trouble the patients, especially during the full range of motions. The question remained as to how many and which surface muscles of the upper arm had to be studied by means of EMGs. For a part of the experiments it was decided that the muscle **TRIlat** was not much informative and because of this its EMGs was replaced with a signal from a 2D goniometer.

Other obstacles in making definite conclusions concerning the changes in the motor apparatus of the post-stroke survivors are the natural differences between different healthy peoples and their left and right hands (Fig. 2, Fig. 3A, Fig. 3B, Table 1). Obviously the working frequencies of different muscles are different; the people’ muscles consist of different percent of slow and fast motor units (depending on sex, training, ages etc.). Independently on our expectations and the statements of other authors [6] the statistical analysis showed that there was no statistical significance of differences of ***MDF*** between dominant and non-dominant hand for healthy people during the one minute fatigue test (Table 3).

Independently of above mention obstacles some inferences can be made from the obtained data.

The results presented in Table 1 and Fig. 1 presume that the working frequencies of the muscles of the injured limb have lower values compared to the healthy limb. Hence, after a stroke the muscles of the affected upper arm work at lower frequency, which implies that their muscles have a greater number of survived slow motor units.

It has to be noted that more of the positive points in Fig. 1A are for the Pat10 (for the muscles **BIC** and **DELacr**) and for the Pat9 (for the muscle **TRIlong**) which affected limbs are the left ones, but the dominant limbs are the right ones. Namely, the most positive values are found for patients with left injured limb. For the end of the posture maintenance (Fig. 1B) the ranges of the differences become smaller, the points migrates closer to zero line. Exceptions are the Pat2 and Pat7 for which the differences MDF_{RH}-MDF_{LH} for the muscle **TRIlong** become more negative. These two patients had a tremor – involuntary muscle contractions and oscillations or twitching movements during relaxation. For the Pat2 and Pat4 the difference MDF_{RH}-MDF_{LH} for the muscle **BIC** had the biggest negative values. They can not complete exactly the “fatigue” task because they let their injured upper hand to fall a bit before one minute duration. The range of the plotted values in Fig. 1 for m. **BIC** and m. **TRIlong** is very wide, probably because these muscles are two-joint ones and participate in supporting the stability both of shoulder and elbow joint.

For healthy subjects, for both beginning and end of the “fatigue” task, the values of MDF_{RH}-MDF_{LH} are distributed nearly symmetrical with respect to the zero line (Fig. 2). The reason could be similar fatigue alterations for dominant and non-dominant limbs.

The measured ranges of shoulder motions in both planes – flexion/extension and abduction/adduction, with and without attached additional load at the wrist, flexing left and right (affected/not affected) elbow, could not be totally generalized using some logical way (Fig. 3). The additional load visually does not uniformly influence the shoulder motions. Probably each movement of each person is unique. When we compare the ranges of motions between patients and subjects it can be seen that the patients have larger amplitudes in the shoulder joint although the given task is flexion in the elbow. This shoulder instability can be due to either a violence of the synchronization between the two-joint muscles or in weakness of the muscle which perform tasks. Probably an additional force is necessary when flexing the elbow joint because of weakness of the main elbow muscles and that is why pendulum assistance in shoulder is helpful for the patients. Similar observation was made in [3, 16] for reaching movements.

It can be concluded from the results shown in Fig. 4 that in general the muscles of the affected limb (especially the m. **BIC**) reach a greater percentage of their maximal possible force than those of the non-affected limb. Hence, patients use more power of the affected limb muscles to perform motions. Similar tendencies can be seen for patients' limbs which are unaffected by stroke, i.e. here also an increase of the percent of the maximal possible isometric force developed by the agonistic muscles is observed, in comparison to the healthy subjects' limbs. This refers to the flexion without load, too. Obviously the muscles of the damaged hand use more percent from their maximal values compared to the healthy people. Especially this refers to the main participant in this movement – the m. **BIC**. It can be seen also that m. **DELcla** have high participation in the task **FSPLoad** with the damaged limb although it is shoulder muscle but the motion is elbow flexion. Table 4 showed that the differences in shoulder range of motion were always statistically significant with the exception of one case – during performing the motion **FSP** with the left hand. This comparison between healthy volunteers and post-stroke survivors shows that the patients use different motion strategy of their upper limb. It cannot be concluded from Fig. 4, however, that the antagonistic co-activation rises in the injured limb, since neither m. **TRIlong**, nor m. **DELspi** increase their activity in the injured limbs. For healthy volunteers the situation for both limbs is rather similar to the distribution shown in Fig. 4B. There were no obvious major differences in the motion strategies between right and left hand for the healthy subjects.

It can also be seen (not shown by the figures) from the calculated values of the ***MDF*** and ***MNF*** for healthy subjects that these values for all muscles expecting **BRD** and **DELcla** decreases for most of the subjects at the end of the task for both limbs. Hence, **BRD** and **DELcla** are the less fatigued. The remaining muscles are more affected by fatigue since they are the muscles that mainly take part in the maintenance of the shoulder during forward flexion of the arm (approximately 90°). Surprisingly, no significant high fatigue was observed for the affected arms of the patients, i.e. ***MDF*** and ***MNF*** do not decrease significantly more for injured arm muscles after one minute posture maintenance. In contrast to the healthy subjects, for most of the patients the m. **DELcla** is more fatigued probably because during the task the shoulder is more abducted and this muscle helps in maintenance of this posture.

Two discussion points concerning the processing of the data would be also discussed. The usually accepted in biomechanics way for normalization of the EMGs with respect to the signal level during maximal isometric contractions [4] is used in this study. However, the maximal isometric force for different people can be reached for different isometric tasks and for different upper limb configurations. Especially this refers to the patients which muscles are weak and sometime maximal power tasks are even painful. For example, we observed that the m. **BRD** can reach its maximal force or during the task "squeezing the balloon of a dynamometer" or during the maximal isometric contractions against resistance. Other point is the way the muscle coordination is investigated. Usually the scientists calculate the start of the muscle activity. We preferred to investigate the maximal forces during two tasks – ***FSP*** and ***FSP+Load*** – since these values as well as the time moments were these maxima were reached could be automatically calculated, whereas the start of the muscle activity depended many on noise and base line.

Conclusions

Upper arm motor deficit in stroke patients has not been very well studied yet, and contradictory results have been reported concerning muscle motor units reorganization, changes in muscles' coordination, coactivation, fatigue, etc., both in stroke-affected and healthy upper arms. Some of these obscurities are due to the natural differences between dominant and non-dominant arm. By means of registered and processed EMGs and two angles in the shoulder joint, we investigated the behavior of muscles of both upper arms for post-stroke patients and healthy volunteers. Statistical analysis was performed on the following parameters: mean and median frequencies at the beginning and at the end of one minute support of the arm in horizontal plane; and the range of the shoulder angles during performing full elbow flexion motions. The main conclusion is that each tested human has their own muscle characteristics (i.e., the median frequencies are within large region for both upper limbs) and their own motor strategies (the sequence of activation and deactivation of the muscles performing flexion in the elbow joint).

Hence, it has been confirmed by our experiments that it is difficult to draw definitive conclusions about the influence of a brain stroke on the muscles' structure and coordination. This is due to several reasons. First, a natural discrimination exists for healthy people between their left and right limbs, which can be, respectively, their dominant and non-dominant ones (Fig. 2A, Fig. 3A and Fig. 3C). Variations also exist between healthy people's muscles, which do not contain the same percentages of the three main types of motor units. Furthermore, each subject has their own individual motion strategy and trained muscle synergies.

Despite this, some general conclusions can be drawn:

(1) the working frequencies of the injured muscles decrease, so it is likely that more slow motor units survive after stroke;
(2) the coordination between the muscles and the joints is awkward and more of the patients evidently use a greater range of shoulder motion to help in performing elbow flexion;
(3) more muscle power in the agonistic muscles is used for performing elbow flexion in the injured limb, but obvious antagonistic co-contraction is not observed.

References

1. Angelova S., R. Raikova, V. Chakarov, H. Aladjov (2013). Estimation of the Upper Arm Motor Deficit in Stroke Patients Using EMG Signals – A Preliminary Study, Series on Biomechanics, 28(1-2), 20-27.
2. Brunnstorm S. (1970). Movement Therapy in Hemiplegia, New York, Harper & Row.
3. Cirstea M. C., A. B. Mitnitski, A. G. Feldman, M. F. Levin (2003). Interjoint Coordination Dynamics during Reaching in Stroke, Experimental Brain Research, 151(3), 289-300.
4. De Luca C. J. (1997). The Use of Surface Electromyography in Biomechanics, Journal of Applied Biomechanics, 13, 135-163.
5. Dewald J. P., V. Sheshadri, M. L. Dawson, R. F. Beer (2001). Upper-limb Discoordination in Hemiparetic Stroke: Implications for Neurorehabilitation, Topics in Stroke Rehabilitation, 8(1), 1-12.

6. Diederichsen L. P., J. Nørregaard, P. Dyhre-Poulsen, A. Winther, G. Tufekovic, T. Bandholm, L. R. Rasmussen, M. Krogsgaard (2007). The Effect of Handedness on Electromyographic Activity of Human Shoulder Muscles during Movement, Journal of Electromyography and Kinesiology, 17(4), 410-419.
7. Farmer S. F., M. Swash, D. A. Ingram, J. A. Stephens (1993). Changes in Motor-unit Synchronisation Following Central Nervous Lesions in Man, The Journal of Physiology, 463, 83-105.
8. Gemperline J. J., S. Allen, D. Walk, W. Z. Rymer (1995). Characteristics of Motor Unit Discharge in Subjects with Hemiparesis, Muscle & Nerve, 18(10), 1101-1114.
9. Graham L. A. (2013). Management of Spasticity Revisited, Age Ageing, 42(4), 435-441.
10. Gray V., C. L. Rice, S. J. Garland (2012). Factors That Influence Muscle Weakness Following Stroke and Their Clinical Implications: A Critical Review, Physiotherapy Canada, 64(4), 415-426.
11. Hu X. L., K. Y. Tong, L. K. Hung (2006). Firing Properties of Motor Units during Fatigue in Subjects after Stroke, Journal of Electromyography and Kinesiology, 16(5), 469-476.
12. Kent T. A., V. M. Soukup, R. H. Fabian (2001). Heterogeneity Affecting Outcome from Acute Stroke Therapy: Making Reperfusion Worse, Stroke, 32(10), 2318-2327.
13. Levin M. F. (1996). Interjoint Coordination during Pointing Movements is Disrupted in Spastic Hemiparesis, Brain, 119(Pt 1), 2812-2893.
14. Mazevet D., S. Meunier, P. Pradat-Diehl, V. Marchand-Pauvert, E. Pierrot-Deseilligny (2003). Changes in Propriospinally Mediated Excitation of Upper Limb Motoneurons in Stroke Patients, Brain, 126(4), 988-1000.
15. McComas A. J., R. E. Sica, A. R. Upton, N. Aguilera (1973). Functional Changes in Motoneurones of Hemiparetic Patients, Journal of Neurology, Neurosurgery and Psychiatry, 36(2), 183-193.
16. McCrea P. H., J. J. Eng, A. J. Hodgson (2005). Saturated Muscle Activation Contributes to Compensatory Reaching Strategies after Stroke, Journal of Neurophysiology, 94(5), 2999-3008.
17. McNulty P. A., G. Lin, C. G. Doust (2014). Single Motor Unit Firing Rate after Stroke is Higher on the Less-affected Side during Stable Low-level Voluntary Contractions, Frontiers in Human Neuroscience, 8, 518.
18. Nudo R. J. (1999). Recovery after Damage to Motor Cortical Areas, Current Opinion in Neurobiology, 9, 740-747.
19. Phinyomark A., S. Thongpanja, H. Hu, P. Phukpattaranont, C. Limsakul (2012). The Usefulness of Mean and Median Frequencies in Electromyography Analysis, Computational Intelligence in Electromyography Analysis – A Perspective on Current Applications and Future Challenges, Ganesh R. Naik (Ed.), 195-220.
20. Quandt F., F. C. Hummel (2014). The Influence of Functional Electrical Stimulation on Hand Motor Recovery in Stroke Patients: A Review, Experimental & Translational Stroke Medicine, 21, 6-9.
21. Raikova R., S. Angelova, V. Chakarov, D. Krastev (2014). An Approach for Experimental Investigation of Muscle Activities of the Upper Limbs (Right Versus Left Arm) of Healthy Subjects and Post-stroke Patients – A Preliminary Study, International Journal Bioautomation, 18(2), 101-110.
22. Silva C. C., A. Silva, A. Sousa, A. R. Pinheiro, C. Bourlinova, A. Silva, A. Salazar, C. Borges, C. Crasto, M. V. Correia, J. P. Vilas-Boas, R. Santos (2014). Co-activation of Upper Limb Muscles during Reaching in Post-stroke Subjects: An Analysis of the Contralesional and Ipsilesional Limbs, Journal of Electromyography and Kinesiology, 24(5), 731-738.

23. Takeuchi N., S. Izumi (2013). Rehabilitation with Poststroke Motor Recovery: A Review with a Focus on Neural Plasticity, Stroke Research and Treatment, Article ID 128641.
24. Tropea P., V. Monaco, M. Martina, F. Posteraro, S. Micera (2013). Effects of Early and Intensive Neuro-rehabilitative Treatment on Muscle Synergies in Acute Post-stroke Patients: A Pilot Study, Journal of NeuroEngineering and Rehabilitation, 10, 103.
25. Wu Y.-N., S.-C. Huang, J.-J. Chen, Y.-L Wang, M. Piotrkiewicz (2004). Spasticity Evaluation of Hemiparetic Limbs in Stroke Patients before Intervention by Using Portable Stretching Device and EMG, Journal of Medical Biological Engineering, 24(1), 29-35.

Prof. Rositsa Raikova, D.Sci.
E-mail: rosi.raikova@biomed.bas.bg

Rositsa Raikova was born in Shoumen, Bulgaria on 16 October, 1955. She received her Ph.D. in Biomechanics in 1993. She then worked in the Institute of Mechanics and Biomechanics at the Bulgarian Academy of Sciences. Now she is a Professor at the Institute of Biophysics and Biomedical Engineering, Bulgarian Academy of Sciences and head of the Department of Biomechanics and control of movements. Her research interests are in the field of biomechanics and motor control of the human limbs.

Silvija Angelova, Ph.D. Student
E-mail: sis21@abv.bg

Silvija Angelova graduated National Sport Academy “Vasil Levski”, Sofia, Faculty of Kinesitherapy, specialization Kinesitherapy in Orthopedic and Traumatology – B.Sc. degree in 2006 and M.Sc. degree in 2008. She started her Ph.D. degree in 2011 in Institute of Biophysics and Biomedical Engineering. Her fields of interests are in bioelectrical activity of muscles in norm and pathology, neuro-muscle diseases, muscle work during sport training.

Senior Assist. Prof. Simeon Ribagin, Ph.D.
E-mail: sim_ribagin@mail.bg

Simeon Ribagin graduated the National Sports Academy “Vasil Levski”, Sofia and obtained his M.Sc. degree in Kinesitherapy in Orthopedics and Traumatology in 2010. From 2010 he is a part-time lecturer at the University of National and World Economy – Sofia. He received his Ph.D. in Informatics and Computer Sciences in 2015 and presently he is a Senior Assistant Professor at Bioinformatics and Mathematical Modeling Department of the Institute of Biophysics and Biomedical Engineering, Bulgarian Academy of Sciences, Sofia. His fields of interests are physical therapy, analysis of movement coordination and force, mathematical modeling of biological processes.